5.0 RISKS AND HAZARDS OF DAM FAILURE

5.1 RISKS OF DAM FAILURE

Risk can be defined as the probability that a dam may fail; no matter how well a dam is built or maintained, the risk of failure cannot be reduced to zero. Hazard describes the probable consequences of dam failure, such as, loss of life and property damage. A dam may have a small risk of failure, but may present a high hazard should failure occur, particularly if a large number of people live within the inundation zone of the dam. Since all dams pose some risk, no matter how small, all dams present a hazard to the public or property. Dam failures are severe threats to life and property and are now being recorded and documented much more thoroughly than in the past. Recorded losses have been high. Life and property loss statistics fully justify the need for dam owners to better understand the risks of failure and the hazards to the public posed by dams, the types of conditions or factors that promote these risks, and, generally, the reasons why dams fail. Improving a dam owner's understanding of risk factors and possible reasons for failure is an essential first step in any overall effort to improve dam safety and preserve the benefits of dam ownership.

The risk factors that can cause dam failure are translated into high risks when people or property are threatened. These risk factors can be classified into one of four categories: 1) structural factors, 2) natural factors, 3) human factors, 4) operating factors.

Structural Factors

The dam structure itself can be a source of risk due to possible design or construction flaws, the size of the dam and the storage area of the reservoir, the complexity of the dam and its appurtenant works, the age and condition of the dam, general foundation and abutment conditions, seepage potential, construction material characteristics, and weaknesses which develop because of aging. Poor embankment design or construction can lead to cracking or sliding of the soils which may result in the uncontrolled discharge of water. Poorly installed embankment materials or spillway structures can lead to serious soil piping or seepage, both of which can lead to uncontrolled loss of water. The site immediately surrounding the structure may also increase structural risk if the dam is not positioned or anchored properly or if excessive reservoir seepage erodes the foundation or abutments. The abutments and foundation may have inherent weaknesses in the form of faulting and rock condition, such as fractures, shear zones, relief jointing and solubility. Some embankment, foundation, or abutment materials have a potential for liquefaction to occur during seismic events. High dams will impose more pressure on the embankment and foundation of the dam which can increase the risk of seepage and slope failure. Reservoirs with inadequate storage capacity can lose their ability to contain flood events by losing storage from sedimentation. Construction material characteristics such as permeability, erodibility, and strength also may present a risk to dam failure if they are inadequate for the dam loading conditions. As dams age, they tend to lose their strength through material deterioration, making them more susceptible to dam failure. All of these conditions pose risks to the dam safety by potentially affecting the structural integrity of the dam, the foundation, or the abutments.

Natural Factors

Natural risks such as floods from high precipitation, floods from dam failures, earthquakes, landslides, and sedimentation are also important contributors to risk. Floods from high precipitation are the most significant natural events that can impact dams and pose a hazard to people and property. Failure to account for these events has been costly both to dam owners and the public in general.

Flash floods can happen anywhere, even in small watersheds. Floods are the most frequent and costly natural events that lead to disaster in the U.S. Therefore, flood potentials must be included in risk analyses for dam failure. Indiana has design flood criteria that are based on a percentage of the probable maximum precipitation (PMP) based on the dam's hazard potential. A PMP is the precipitation that may be expected from the most severe combination of critical meteorologic conditions that are reasonably possible in the region. This assumed event becomes the basis for the design of structural and hydraulic elements of the dam.

When a dam fails as a result of a flood, more people and property are generally placed in jeopardy than during natural floods. The Rapid City, South Dakota flood of 1970, which killed 242 people, caused a dam failure which added significantly to the loss of life. When a natural flood occurs near a dam, the probability of failure and loss of life almost always increases. The sudden surge of water generated by a dam failure usually exceeds the maximum flood expected naturally, therefore, residences and businesses that would escape natural flooding can be at extreme risk from dam failure flooding. When one dam fails, the sudden surge of water may well be powerful enough to destroy another downstream dam, compounding the disaster.

Earthquakes are also significant threats to dam safety. Both earthen and concrete dams can be damaged by ground motions caused by seismic activity. Cracks or seepage can develop, leading to immediate or delayed failure. Recent detailed seismic analyses have indicated that the seismic risk is essentially nationwide. Dam owners should be aware of the history of seismic activity in their locality and should develop their dam safety emergency procedures accordingly.

Indiana has several faults, but, unlike California's famous San Andreas Fault, nearly all of Indiana's faults are buried and can't be seen at the surface. Most of the faults that have been mapped in Indiana are located in the southwestern corner of the state. These faults extend into Illinois and are collectively known as the Wabash Valley Fault System. These mapped faults are believed to be unlikely candidates for future movement. The earthquakes that have occurred in Indiana during the last 200 years are believed to be the result of movement along faults at great depth below the surface. This depth and the nature of the rock layers at that depth have limited the ability of seismologists to successfully map earthquake-generating faults using reflection seismic profiling. Much more research is needed before we will know the full extent of faulting beneath Indiana and the potential for movement along those faults.

During the last two centuries, earthquakes with epicenters in Indiana have been relatively minor events. However, this has not always been the case. Indiana University archaeologists Pat Munson and Cheryl Munson, and U.S. Geological Survey geologist Steve Obermeier have found evidence of at least 6 major earthquakes with epicenters in Indiana during the last 12,000 years. The largest of these quakes appears to have had an epicenter near Vincennes and has been estimated to have been many times more powerful than the quake that struck the Los Angeles area in January 1994.

The New Madrid fault in what is now southeastern Missouri experienced movement on December 15, 1811, that produced shock waves that rippled through the earth with such force that buildings collapsed, trees toppled, and the Mississippi River changed course. The result was one of the most powerful earthquakes ever recorded in North America. During the next two months, the area was rocked by three more quakes as powerful as the first (one just six hours after the first) and hundreds of smaller ones. The larger quakes shook the earth with enough force to cause church bells to ring in Washington, D.C. They were felt in Indiana and were even felt a thousand miles away in New Hampshire.

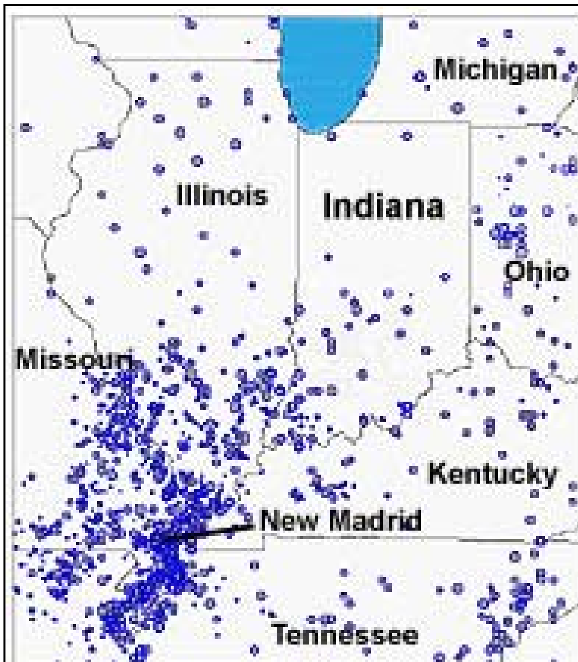

Figure 5-1 Earthquake epicenters in Indiana and neighboring states from 1800 to 1995 (source: Indiana Geological Survey).

Since the New Madrid quakes, Indiana has felt the effects of many earthquakes (see figure 5-1). The strongest of these was the 1895 Charleston, Missouri quake, which damaged buildings in Evansville and other parts of southwestern Indiana. According to the U.S. Geological Survey, the strongest quake centered in Indiana during historic times struck the Wabash River valley on September 27, 1909. This quake knocked down chimneys, broke windows, and cracked plaster in the lower Wabash Valley and was reportedly felt in Arkansas, Illinois, Iowa, Kentucky, Missouri, Ohio, and Tennessee. More recently, Indiana was shaken in 1987 by a quake centered near Olney, Illinois, just west of Vincennes.

Rock slides and landslides may impact dams directly by blocking a spillway or by eroding and weakening abutments. Indirectly, a large landslide into a reservoir behind a dam can cause an overflow wave which will exceed the capacity of the spillway and lead to failure. A land (or mud) slide can form a natural dam across a stream which can then be overtopped and fail. In turn, failure of such a natural dam could then cause the overtopping of a downstream dam or by itself cause damage equivalent to the failure of a human-made dam. In addition, large increases in sediment caused by slides (or runoff) events can materially reduce storage capacity in reservoirs and thus increase a downstream dam's vulnerability to flooding. Sedimentation can also damage low-level gates and water outlets; damaged gates and outlets can lead to failure.

Human Factors

Human behavior is another element of dam failure risk; simple mistakes, operational mismanagement, unnecessary oversights, or destructive intent can interact with other hazards to compound the possibility of failure.

All sorts of other human behavior should be included in risk analyses. Vandalism for example cannot be excluded and is, in fact, a problem faced by many dam owners. Vegetated surfaces of a dam embankment, mechanical equipment, manhole covers, and rock riprap are particularly susceptible to damage by people. Every precaution should be taken to limit access to a dam by unauthorized persons and vehicles. Dirt bikes (motorcycles) and four-wheel drive vehicles, in particular, can severely degrade the vegetation on embankments. Worn areas lead to erosion and more serious problems. Mechanical equipment and associated control mechanisms should be protected from purposeful or inadvertent tampering. Buildings housing mechanical equipment should be sturdy, have protected windows, heavy duty doors, and should be secured with deadbolt locks or padlocks. Detachable controls, such as handles and wheels, should be removed when not in use and stored inside the padlocked building. Other controls should be secured with locks and heavy chains where possible. Manhole covers are often removed and sometimes thrown into reservoirs or spillways by vandals. Rock used as riprap around dams is sometimes thrown into the reservoirs, spillways, stilling basins, pipe spillway risers, and elsewhere. Riprap is often displaced by fishermen to form benches. The best way to prevent this abuse is to use rock too large and heavy to move easily or to slush grout the riprap. Otherwise, the rock must be regularly replenished and other damages repaired. Regular visual inspection can easily detect such human impacts.

Two extremes of human purpose can both result in public risks: 1) the will to destroy through war or terrorism, and 2) the urge to develop and to construct. Dams have proven to be attractive wartime targets, and they may be tempting to terrorists. On the other hand, a terrorist's advantage from holding the public at risk may well be illusory; the deliberate destruction of a dam is not at all easy to bring about. Yet the possibility exists that such an act could take place, and it should not be discounted by the dam owner. Another more common activity that poses a risk is the tendency for people to settle below dams. The construction of residences, buildings, and other structures in the potential flood inundation zone creates new risks, and will probably create increased risks in the future.

Operating Factors

Operating factors that could pose a risk to dam failure, and thus, create a safety hazard to people and property include the remoteness and accessibility to the site, lack of operator training or experience, poor dam maintenance procedures, lack of an inspection program, reliability of power for electrical equipment, and the complexity of the equipment and operating procedures at the dam.

Thus, a broad range of natural and human hazards exist that, taken separately or in combination, increase the probability of dam failure and injury to people and property.

5.2 TYPES AND CAUSES OF DAM FAILURE

Dam failures are usually the result of improper design or construction, or poor maintenance. Dam failures are categorized into two types in this manual: **Type 1**, component failure of a structure that does not result in a significant reservoir release; and, **Type 2**, uncontrolled breach failure of a structure that results in a significant reservoir release.

Figure 5-1 Type 1 component failure.

Type 1 failures include localized seepage and structural failures of dam components that do not breach the dam into the reservoir. Type 1 failures are generally local failures of a dam feature, such as an embankment slide that does not breach the crest, a spillway structural failure, a piping condition in its early stage of formation, a trash rack failure, or settlement on an earth dam embankment that does not extend to the water level. Type 1 failures are critical, require immediate attention, and may lead to a Type 2 failure. Type 1 failures may also require emergency response, reservoir drawdown, or remedial correction.

Figure 5-2 Type 2 uncontrolled breach failure. This started as a seepage failure and progressed to a structural failure of the dam.

Type 2 failures are failures that do result in a significant release of the reservoir and may eventually result in a dam breach with total release of the reservoir. There are three general categories of Type 2 failures: (1) hydraulic failures, (2) seepage failures, and (3) structural failures. Type 2 failures often result from Type 1 failures that were improperly corrected or were ignored.

There are many complex reasons for dam failure, including both structural and nonstructural. Many sources of failure can be traced to decisions made during the design and construction process and to inadequate maintenance or operational mismanagement. Failures have also resulted from the natural hazards already mentioned, such as large scale flooding and earthquake movement.

The United States Bureau of Reclamation Research has shown that approximately one-third of all uncontrolled breach failures are a result of overtopping due to inadequate spillway capacity. Another one-third of dam failures are caused by uncontrolled seepage through the embankment or foundation. The remaining one-third of dam failures is caused by foundation failures and other miscellaneous causes. This summary is highly simplified, and in reality, most dam failures result from a combination of events.

Overtopping may develop from many sources, but often evolves from inadequate spillway design. Alternatively, even an adequate spillway may become clogged with debris. In either situation, water flows over other sensitive parts of the dam, such as abutments or the dam crest, and erosion and failure follow. Concrete dams are more susceptible to foundation failure than overtopping, whereas earthfill dams suffer more from seepage and piping.

The major reason for failure of fill or embankment dams is piping or seepage. All earthen dams exhibit some seepage; however, this seepage can and must be controlled in velocity and amount. Seepage occurs through the structure and, if uncontrolled, can erode material from the downstream slope or foundation backward toward the upstream slope. This "piping" phenomenon can lead to a complete failure of the structure. Piping action can be recognized by an increased seepage flow rate, the discharge of muddy or discolored water below the dam, sinkholes on or near the embankment, and a whirlpool in the reservoir.

Earth dams are particularly susceptible to hydrologic failure since most soils erode at relatively low water flow velocities. Hydrologic failures result from the uncontrolled flow of water over the dam, around the dam, adjacent to the dam, and

Table 1-1
Types of Dam Failures

Type 1 - Component Failure

- Localized, does not breach dam
- Insignificant release of reservoir water
- Types
  1. Seepage failure
     - Pervious reservoir rim or bottom
     - Pervious foundation
     - Pervious dam
     - Leaking conduits
     - Cracks in dam
     - Seepage erosion
     - Inappropriate vegetation
  2. Structural failure
     - Dam or foundation slides and sloughs
     - Dam settlement
     - Spillway cracks or failure
     - Severe erosion

Type 2 – Uncontrolled Breach Failure

- Results in dam breach
- Significant or total release of reservoir water
- Types
  1. Hydraulic failure
     - Dam overtopping
     - Wave erosion
     - Dam toe erosion
     - Severe erosion
  2. Seepage failure
     - Pervious reservoir rim or bottom
     - Pervious foundation
     - Pervious dam
     - Leaking conduits
     - Cracks in dam
     - Piping through dam or along conduits
     - Inappropriate vegetation
     - Windblown trees
     - Animal burrows
  3. Structural failure
     - Dam and foundation slides
     - Dam failure
     - Dam settlement
     - Spillway cracks or failure

the erosive action of water on the dam's foundation. Once erosion has begun during overtopping, it is almost impossible to stop. In a very special case, a well-vegetated earth embankment may withstand limited overtopping if water flows over the top and down the face as an evenly distributed sheet and does not become concentrated in a single channel.

Failure of concrete dams is primarily associated with foundation problems. Overtopping is also a significant cause, primarily because of spillways with inadequate capacity. Earthquakes and poor concrete design or construction may also result in failure of concrete dams.

5.3 NOTABLE DAM FAILURES

Earthen Dam Failures

South Fork Dam, Pennsylvania

South Fork Dam was an embankment dam built across the Conemaugh River, about 9 miles above Johnstown, Pennsylvania, between 1838 and 1853. The purpose of the dam was to supply water to a navigable canal from Johnstown to Pittsburg. The dam was 70 feet high and impounded 12,400 acre-feet. The dam was modified by closing off the outlet pipes, building a bridge over the spillway, installing a road on the embankment crest, and lowering the embankment by 3 feet. A fish screen was also installed in front of the spillway to keep the fish from passing over the spillway. A very heavy rainstorm occurred on May 30 and 31, 1889. The reservoir filled and the spillway went into operation. A large amount of debris was washed into the reservoir and moved toward the spillway where it became lodged against the fish screen. The reservoir continued to rise as the spillway was largely blocked. Attempts to clear the spillway were unsuccessful, and eventually the dam was overtopped. The dam subsequently failed by erosion releasing a flood wave estimated to be 30 to 40 feet high. The flood moved down the narrow valley of the Conemaugh River toward Johnstown and other smaller communities, which were already experiencing flooding from the rainfall. The flood wave swept through Johnstown in about 10 minutes. The devastation was tremendous. Altogether, the death toll was estimated at 2,209, making this one of the worst disasters in terms of loss of life in United States history. It was later calculated that if a spillway had been built according to specifications and if the original outlet pipes had been available for full capacity discharge, there would have been no overtopping.

Teton Dam, Idaho

Teton Dam was a 305-ft high central core, zoned, earth and gravel fill embankment designed by the Bureau of Reclamation and completed in November 1975. The dam was located on the Teton River in eastern Idaho. The Teton Dam failed on June 4, 1976, when reservoir filling was nearly complete. The failure was attributed to (1) internal erosion (piping) of the core of the dam deep in the right abutment foundation key trench, with the eroded soil particles finding exits through channels in and along the interface of the dam with the highly pervious abutment rock and talus to points at the right groin of the dam; (2) destruction of the exit avenues and their removal by the out-rush of reservoir water, (3) the existence of openings through inadequately sealed rock joints which may have developed through cracks in the core zone in the abutment key trench; (4) the development of piping through the main body of the dam that quickly led to complete failure; and (5) the design of the dam did not adequately take into account the foundation conditions and the characteristics of the soil used for filling the abutment key trench. Flooding downstream inundated the communities of Rexburg and Sugar City, Idaho, among others, and 11 people were killed. Property damage was in excess of half a billion dollars.

Fontenelle Dam, Wyoming

Fontenelle Dam is a zoned earthfill embankment located on the Green River in Western Wyoming. The dam was completed in 1964, and is 128 feet high and over 1 mile long. A cutoff trench extends to bedrock and a grout cap and line of grout holes was drilled along the centerline of the trench. During construction, several open joints and cracks were encountered in the area of the spillway intake. These cracks angled into the abutment in a downstream direction. A line of grout holes was added around the spillway intake to restrict seepage through the foundation in this area. Also, an impervious blanket was extended upstream along the lower part of the abutment. No foundation surface preparation was done to seal the foundation in contact with the embankment. Embankment material was placed directly over the open joints and cracks in the foundation rock. As the reservoir began to fill, a seep occurred about 2,000 feet downstream of the dam. Seepage continued to increase as the reservoir level rose. On September 3, 1965, when the reservoir was nearly full, a seep appeared on the downstream slope of the dam. Within one day, the seep worsened and removed 10,000 cubic yards of soil from the embankment. A 30 feet deep sinkhole developed on the crest the following day. Repair operations, consisting of rebuilding the damaged embankment section, and extensive grouting, and a concrete diaphragm cutoff wall eventually solved the seepage problem and averted an uncontrolled breach failure. The seepage had come through the rock joints in the abutment and exited on the downstream slope, causing the near disastrous failure.

Baldwin Hills Dam, California

The Baldwin Hills Dam was constructed between 1947 and 1951 in the city of Los Angeles. Located on a ravine, the reservoir was formed by a continuous homogeneous compacted embankment, with the maximum section being 232 feet high. The Baldwin Hills Dam failed on December 14, 1963 following displacement of its foundation. The displacement created a 3-ft wide crack in the embankment, causing seepage and eventual breaching. The reservoir was completely drained in 2 hours. At least 2 theories for the failure have been proposed. It has been speculated that pressurization of the nearby oil field caused movement along one of the faults passing beneath the reservoir. Others believe that differential settlement occurred along one of the faults due to the fractured and loosened nature of the fault zone material. Five people were killed by the flood waters and nearly 1,000 homes were damaged. Total property damage was over $11 million.

Lawn Lake Dam

The Lawn Lake Dam was a 24-ft high earthfill dam built in 1903 in the Rocky Mountains of Colorado at an elevation of almost 11,000 feet. The dam was owned and operated by a private irrigation company. Early on the morning of July 15, 1982, the dam failed releasing 700 acre-feet of water at a peak discharge of 18,000 ft^3/s. The flood waters raced down the steep Roaring River channel scouring it to a depth of as much as 35 feet and into the broad flat valley of the Fall River. There the flood waters were briefly impounded by Cascade Dam, a 17-ft-high concrete gravity dam. Eventually, Cascade Dam was overtopped by more than 4 feet and also failed. The damages from the failure totaled $31 million and three people were killed. The probable cause of the failure was believed to be the deterioration of the lead caulking used to seal the connection between the upstream outlet-works pipe and the valve housing. As a result, water under reservoir head was able to enter the fill and rapid progressive internal erosion, or piping, led to a breaching of the dam.

Kelly Barnes Dam

The Kelly Barnes Dam on Toccoa Creek near Toccoa, Georgia, was about 400 feet long, 20 feet wide at the crest, and 42 feet high at the maximum section. The dam was concave upstream. The lake had a normal impoundment of about 18 million cubic feet (410 acre-feet) and a surface area of about 42 acres. The lake level rose by approximately 4.5 feet before the dam failed, and the water volume increased to about 27 million cubic feet. The Kelly Barnes Dam failed at approximately 1:30 a.m., November 6, 1977, after a period of intensive rain. Thirty-nine people were killed and damages were estimated at $2.8 million.

The dam went through various stages of development: first as a rock crib dam, and then with subsequent stages as an earth dam. The rock crib dam was completed about 1899 to back up water which would be used to power a small hydroelectric plant located near the foot of the falls. About 1937, the Toccoa Falls Bible Institute was interested in developing a more dependable power source and decided to build an earth dam over the rock crib dam. This construction was performed with equipment provided by a local manufacturer. After World War II, the earth fill was raised to a point where an earth spillway on the left side of the valley could be utilized, and a low point on the rim on the right side away from the dam would serve as a secondary spillway in case high flows occurred. The final height of the dam was approximately 42 feet above the rock foundation. This installation served as a power source until 1957 for the Toccoa Falls Bible Institute, which later became the Toccoa Falls College. At this time, the development of power was stopped but the dam continued to be used as a recreation lake.

The Federal Investigative Board could not determine a sole cause of the November 6, failure. It did conclude that a combination of factors caused the failure. The most probable causes were a local slide on the steep downstream slope, probably associated with piping, an attendant localized breach in the crest followed by progressive erosion, saturation of the downstream embankment, and subsequently a total collapse of the structure.

Buffalo Creek Dam

On February 26, 1972, the Buffalo Creek (tailings) Dam in West Virginia failed, causing a flood wave that killed 125 people and left another 4,000 homeless. The embankment, which consisted of a pile of coal mine waste, impounded the reservoir but lacked the features of an engineered dam. It was part of a system of spoil embankments and sediment basins on a tributary of Buffalo Creek. Waste had been accumulating for about 25 years before the failure. The piles consisted of shale, sandstone, low-grade coal, and various kinds of timber and metal scrap. By 1960, the first embankment had been extended to a length of approximately 1200 feet, a width of roughly 500 feet, and a height of approximately 150 feet. This embankment had evidently burned for many years. In about 1960, the mining company, to reduce stream pollution, began to run waste water from its plant into the impoundment behind the embankment. The material from this source was naturally finer than the embankment material and tended to seal the embankment. The seepage slowed, and the reservoir level rose. Federal inspectors visited the complex in 1966 and reportedly called attention to the precarious condition of the embankment. In 1967, a new embankment was constructed 600 feet upstream from the first barrier. Then, in 1970, a third fill was placed 600 feet upstream from the second. The result was a staircase of poorly built embankments, with the upper two founded on the soft sediment in the settling basins. By 1972, the newest of the three embankments was roughly 500 feet in length and had risen about 44 feet above the sediment in the middle pool. Its broad crest was nearly as wide as it was long. A 24-inch steel overflow pipe was reportedly installed in July 1971, which extended diagonally through the fill from one side toward the center. Aside from this, the reservoir had neither spillway nor outlet. The pipe evidently did not have an inlet structure or any cutoff collars.

Occasional slips and breaks had occurred during the lifetime of the embankments. In 1971, a mining company worker said that he had seen black water issuing from the floor of the middle pool, indicating leakage through or under the uppermost dam. In the three days preceding the failure, about 3.7 inches of rain fell in the area. Storm runoff caused the reservoir behind the third dam to rise. The water level reportedly was within 1 foot of the crest 4 hours before the collapse. Between 6 and 8 a.m. on that day, the water rose onto the graded crest and washed through dumped waste that stood as high as 7 feet above the crest. A mining company employee reportedly was dispatched at 6:30 a.m. to find bulldozers for excavation of an emergency spillway, but the equipment never reached the site. Longitudinal cracks appeared in the soggy fill. Slumping of the downstream face dropped the crest and accelerated the overflow. The dam broke at about 8 a.m. The upper pool had contained approximately 40O acre-feet of sludge and water, which was completely discharged within a quarter of an hour. During the next 3 hours, a flood wave estimated as high as 20 feet moved down the 15 miles of the Buffalo Creek valley at about 5 miles per hour. The village of Saunders at the upper end of this reach was washed out, and extensive damage was done to several other settlements downstream.

Canyon Lake Dam

One of the most intense floods in American history struck South Dakota's Black Hills on

June 9, 1972, and destroyed much of Rapid City, a community of 43,000 people. Canyon Lake was a 40-acre reservoir west of Rapid City. Canyon Lake Dam was an earthen embankment approximately 20 feet high and 500 feet long, constructed by the Works Progress Administration in 1938. The cause of the disaster was a violent rain-storm which developed suddenly. Beginning early in the evening and continuing into the night, as much as 10 inches of rain fell on a watershed where the normal annual precipitation was only about 14 inches. Runoff accumulated rapidly on the steep rock slopes and gained velocity in the narrow canyons on its way to the populated areas to the east. Rapid Creek was discharging an estimated 30,000 cubic feet per second into Canyon Lake. Floodwaters were rising fast against the 20-foot high earth dam. At approximately 8:30 p.m., spillway releases were made in an attempt to control the lake level. Beginning at about 9 p.m., a cloudburst brought as much as 6 inches of rain in 2 hours. Rapid Creek broke out of its banks. The mayor and the city engineer of Rapid City inspected the Canyon Lake Dam just before 10 p.m. Men from the police and fire departments were dispatched to warn people downstream from the reservoir. Many residents underestimated the danger at first and remained in their homes. Water was surging down the streets.

Near 10:30 p.m., the Canyon Lake Dam spillway was obstructed by debris and the embankment was on the verge of overtopping. The storm water began to overtop the dam and began to scour the embankment. The muddy torrent pouring from the reservoir overwhelmed the winding channel of Rapid Creek all the way through the city. At about 10:45 p.m., the dam washed out. The water and debris disgorged through the breach. When the Canyon Lake Dam collapsed, the surge of debris-laden water struck Rapid City with full force. Buildings near the creek were shattered. Many of the occupants were unable to escape. Mobile homes and trailers were washed away. Powerlines were knocked down and propane tanks were ruptured. There were many fires and explosions. Natural gas escaped from broken pipelines and burst into flames from the sparks of the downed powerlines. The final toll was 237 fatalities, 5 persons missing, and 5,000 homeless in the path of the flood. More than half of Rapid City was said to be devastated. Twelve hundred houses were demolished, and 2,500 others were extensively damaged. About 100 commercial and industrial buildings had been ruined. Approximately 5,000 wrecked automobiles were scattered throughout the city. Seven of the nine bridges which had spanned Rapid Creek, 80 blocks of street, and 5.5 miles of railroad trackage were reported to have been destroyed. Total property damage was estimated at $60 million.

Concrete Dam Failures

Austin, Pennsylvania

An example of a foundation problem can be found in the failure of the Austin, Pennsylvania Dam in September, 1911. The concrete gravity dam was constructed in 1910 and was designed to contain 600 acre-ft of water. Shortly after reservoir filling began, the dam dropped about 6 inches at the toe and slid out about 18 inches at the spillway. Reservoir filling continued. On September 30, 1911 the dam suffered failure as portions of the dam slid along the base and/or fell on their downstream face.

Eventual failure occurred because of weakness in the foundation or in the bond between the foundation and the concrete. The death toll was estimated at 87.

Walnut Grove, Arizona

In 1890 the Walnut Grove dam on the Hassayompa River failed due to overtopping, killing about 150 people. The failure was blamed on inadequate capacity of the spillway and poor construction and workmanship. A spillway 6 X 26 feet had been blasted out of rock on one abutment, but with a drainage area above the dam site of about 500 square miles, the spillway could not provide nearly enough discharge capacity.

St. Frances Dam, California

The St. Francis Dam was a 205-ft high concrete gravity arch dam built in 1926. The dam impounded a reservoir of 38,000 acre-feet. The design of St. Francis Dam was suspect. The dam was raised twice during construction by a total of 20 feet or 11 percent of its design height without widening the base. The failure of the St. Francis Dam (part of the water supply system for Los Angeles) was also attributed to a variety of problems related to foundation pressures, seepage around the foundation and operation. St. Francis Dam failed suddenly just before midnight on March 12, 1928. The reservoir was nearly full at the time and emptied in about 70 minutes. The failure not only removed most of the dam, but large sections of the foundation as well. The flood wave traveled 9 miles down San Fancisquito Creek and then another 40 miles down the Santa Clara River to the Pacific Ocean. Between the dam and the ocean, 450 people in towns and construction camps were killed. A recent analysis of the failure concluded that the failure initiated with downslope movement of the left abutment leading to tension cracks in the upstream face of the dam causing destabilizing uplift pressures within the dam and subsequent collapse. Seepage through the abutments prior to the failure had been reportedly muddy, suggesting that foundation material was being removed, but the cloudy water had been dismissed by the dam's designer as originating from a nearby construction site.

Vaiont Dam

The Vaiont Dam in Northern Italy is a thin-arch concrete dam built in the late 1950's and filled in 1959; the dam is 850 feet high. In 1960, a relatively small slide of some 1.3 million yd^3 occurred on the left abutment near the dam. At this time, it was discovered that creep was occurring over a much larger area on the left abutment. In 1960-1961, a bypass tunnel was driven through the right abutment for a distance of 1¼ miles. This was done to assure that water could reach the outlet works in case of future slides. Also, as a precaution, after the 1960 slide the reservoir was limited to a maximum elevation of 2,230 feet. This reservoir elevation was about 145 feet below the top of the dam. Gravitational creep on the left reservoir slope continued during the 1960-1963 period. Movements of up to 10 to 12 inches per week were observed on occasion. In early October 1963, following weeks of heavy rains, engineers realized that all the observation stations on the left abutment were moving together as a "uniform unstable mass." On October 8, the engineers began to lower the reservoir, however, because of the heavy inflow from rainfall and the movement of the huge slide mass into the reservoir, the level of the reservoir actually rose. On the evening of October 9, 1963, a massive rock slide occurred on the left abutment immediately upstream from the dam. Over 300 million yd^3 slid into the reservoir, filling the reservoir for 1¼ miles upstream from the dam to depths of over 1,000 feet. This all occurred within a period of 15 to 30 seconds. The dam was overtopped by a 330-foot wave which headed down the narrow canyon toward the city of Longarone, about a mile downstream from the dam. The flood wave was over 230 feet high at the mouth of Vaiont Canyon and hit Longarone head on. Everything in its path was destroyed. Over 2,600 people were killed by the flood. The slide created strong earth tremors which were recorded in Brussels, over 500 miles away. Remarkably, the dam sustained no damage to the main shell or abutments. However, the dam can no longer be used because the cost of removing slide material is too great. The slide was caused by a combination of factors including:

1. adverse geologic features in the reservoir area
2. man-made conditions imposed by impounding water with bank storage, affecting the otherwise delicately balanced stability of a steep rock slope
3. progressive weakening of the rock mass with time, accelerated by excessive groundwater recharge (2 weeks of rain)